

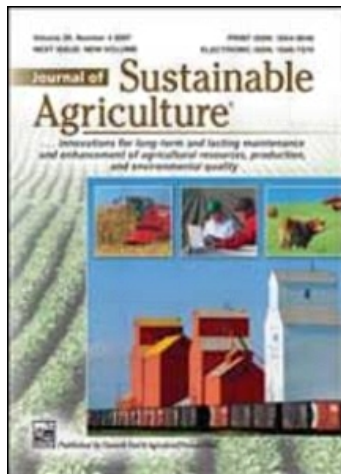
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# Optimal Levels of Irrigation in Corn Production in the Southeast Coastal Plain

Yao-Chi Lu  
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**ABSTRACT.** Water is a precious resource and is used in many competing industries. To use water efficiently in crop production, knowledge about crop responses to irrigation water, or the production function, is essential. In this paper, we estimated six production functions, two N-fertilizer treatments for each year in 1999, 2000, and 2001, for corn production using the data from experimental plots in Florence, South Carolina, USA. Optimal levels of irrigation and gross margins under profit-maximizing and yield-maximizing strategies were computed. The results indicate that at the current prices of corn and water in South Carolina, the profit-maximizing strategy conserved more irrigation water and produced larger gross margins than the yield-maximizing strategy. The differences in optimal levels of irrigation water and gross margins between the two strategies became even more significant when the relative water/corn price ratios increased. To find out how demand for irrigation water responds to changes in water prices, demand functions for water were derived and demand elasticities of water were computed. At the current prices of water and corn, the demand elasticities were inelastic, which means that irrigation is not very responsive to changes in the price of water. As the price of water increased, demand for irrigation became more responsive to changes in water prices. *[Article copies available for a fee from The Haworth Document Delivery Service: 1-800-HAWORTH. E-mail address: <docdelivery@haworthpress.com> Website: <<http://www.HaworthPress.com>>]*

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**KEYWORDS.** Water conservation, water production function, site-specific irrigation, profit-maximization, yield-maximization

## ***INTRODUCTION***

Water is used in many competing industries, and its supply is limited in most irrigation projects. To use water efficiently in crop production, knowledge about crop responses to irrigation water, or the production function, is essential. The production function can be used to determine the level of irrigation that maximizes profits. It can also be used to allocate the water resource among competing uses, allocate irrigation decision among competing crops within the agricultural sector, adjust irrigation rates, and estimate the effect of pricing policies on the agriculture sector (Kulshreshtha et al., 1990).

Hoyt (1982) estimated water production functions of corn, sorghum, and wheat by growth stage in the Texas High Plains region to provide information for farm level irrigation decision to increase profits and for water conservation policy to lengthen the life of the Ogallala Aquifer. Using corn data from a 2-year experiment, Hoyt (1984) estimated water production functions in Colorado and computed yield-maximizing level of water and the profit-maximizing level of water. Hexem and Heady (1978) estimated various water production functions in the Western United States for major crops and livestock for a range of locations, soils, and environmental conditions. They attempted to estimate full generalization of production functions so that they can be used to predict crop yields and to use water more efficiently for irrigation under a range of soils and climatic conditions. Holzapfel et al. (1998) estimated water production functions in Kiwi to provide information for water management and the design of irrigation systems.

The objective of this paper is to estimate water production functions for corn production using the data from experimental plots in Florence, South Carolina, U.S.A., from 1999 through 2001 and to determine the optimal levels of irrigation water that maximize profits and conserve water.

## ***MATERIALS AND METHODS***

### ***Specifications of Production Functions***

Before estimating a production function, we need to specify the algebraic form of the production function and determine which variables must be aggregated and how might such aggregation be carried out (Heady and Dillon, 1961). Many algebraic functional forms have been used as production functions. Griffin (1984) identified 16 functional forms: linear, quadratic, cubic,

square root, logarithmic, Mitscherlich, Spillman, Cobb-Douglas, transcendental, resistance, modified resistance, CES (constant elasticity of substitution), generalized Leontief, translog, generalized quadratic, and generalized power functions. However, not all forms are suitable for biological and economic analysis. The properties of the production function have to be compared with *a priori* plant-water-soil relationships to evaluate the applicability and appropriateness of alternative production functions (Hexem and Heady, 1978). Functional forms that relate crop yield with the amount of irrigation water must demonstrate increasing yield over a particular range of input levels, a peak yield at a certain input level, and decreasing yield over a range of input levels. Only six forms have this property. Of these, the ones most frequently used for estimating water production functions are the quadratic and square root functions. Many studies have indicated that the quadratic function is most appropriate for water production functions. Stewart et al. (1973) showed that the functional relation between yields and the seasonal irrigation depth of the field water supply was convex or quadratic. In analyzing data from several irrigation experiments with grain sorghum, winter wheat, and soybeans, Musick et al. (1976) found that a second-degree polynomial (i.e., quadratic function) fit the data well. Barrett and Skogerboe (1978), working with corn, found a convex relationship between water supply and both dry-matter and grain yield. In the study of seed potato production, Watkins et al. (1998) found that quadratic functions provided the best fit for the data. We also confirmed with our data that quadratic functions were most appropriate based on the R squared. In this study, we used the quadratic form to estimate six production functions: two N-fertilizer treatments for each of the three years.

### ***Irrigation Treatments***

Vaux and Pruitt (1983) divided the economic studies of water production functions into two categories. The first category follows conventional economic theory that ignores the timing of water application. It assumes that the timing of water applications is always optimal. The second category includes the effect of timing, and tends to be more theoretical than empirical. In Hexem and Heady's (1978) studies, the effect of timing was implicitly considered. For most experiments, tensiometers were used to measure soil moisture tension, which was used to determine the need for irrigation. Whenever soil moisture tension rose to a predetermined level, sufficient irrigation water was applied to restore soil moisture to the field capacity level. In estimating water production functions, the input of irrigation water is the quantity of water applied at each irrigation, aggregated to total water applied during the growing season. Therefore, a specific irrigation scheduling regime is implicit in the model (Hexem and Heady, 1978).

In this study, tensiometers were also used to determine irrigation scheduling. Four irrigation treatments were 0, 50, 100, and 150% of an irrigation base

rate (IBR) determined by soil water potential value and meteorological conditions. Soil water potential was measured using tensiometers at two depths (30 and 60 cm). Irrigation was initiated in all irrigation treatments when mean soil water potential value at the 30-cm depth in the 100% base rate treatment was less than or equal to 230 kPa (Sadler et al., 2002). Thus, optimal irrigation scheduling is implicitly included in the amount of irrigation water.

### *Source of Data*

The data were obtained from an experiment conducted at the site-specific center pivot irrigation facility at Florence, SC, USA, during the 1999-2001 corn growing seasons. Irrigation and N treatments were imposed using a commercial, three-span center pivot irrigation system that had been modified to provide site-specific water and fertilizer applications. The experimental design was a  $4 \times 2$  factorial randomized complete blocks (RCBs) where sufficient area existed within soil map unit boundaries as delineated by USDA-NRCS on a 1:1200 scale. Where insufficient area was available, randomized incomplete blocks (RICBs) were used. On larger soil map areas, multiple RCBs were imposed. The number of RCB blocks was 39, of RICB, 19, resulting in a total of 396 plots. The plot sizes were nominally  $9.1 \text{ m} \times 9.1 \text{ m}$  at the outer boundaries and  $6 \text{ m} \times 6 \text{ m}$  in the central control area. Treatments were imposed continually on the same plots, so yield responses reflect the cumulative effects of water or nutrient excesses or deficits. Conventional surface tillage culture was used. Corn ('Pioneer 3163') was planted around the pivot circle with a 6-row planter that had in-row subsoilers to a depth of 40 cm. Row spacing was 0.76 m, and the final plant populations in the three years ranged from about 64,000 to 66,000 plants/ha.

The two N-fertilizer treatments were the recommended rainfed and irrigated rates (135 and 225 kg/ha) corresponding to target yields of 6.3 and 10.1 Mg/ha. Urea ammonium nitrate with sulphur (UAN 24S) was applied according to the treatment plan via the irrigation system.

Each year, a 6.1 m length of two rows near the center of each plot was harvested using a plot combine. The harvested grain was weighed, corrected to 15.5% moisture, and expressed per unit ground area. A detailed description of this experiment is described in Sadler et al. (2002). The data used for this economic analysis was the subset corresponding to the NkA soil, which is the most prevalent soil in the field and the surrounding area.

Gross margins, defined as total returns minus total variable costs, are used to measure profitability. The cost data were obtained from the enterprise budget of the Clemson Extension Service, Clemson University (2002). The variable costs include costs of seeds, fertilizers, lime, herbicides, insecticides, irrigation, drying and hauling, operation of tractors and machinery, labor, and interest on operating capital. The irrigation cost was estimated at \$4/acre-inch, or 39 cents/ha-mm. The price of corn was obtained from USDA Agricultural

Statistics (2002). In the last 20 years, the price of corn has fluctuated from \$1.50/bushel (\$59/Mg) in 1986 to \$3.24/bushel (\$128/Mg) in 1995. The USDA Economic Research Service (2002) estimated the 2001-2002 season average at \$1.85 to \$1.95/bushel (\$73-77/Mg). The Farm Security and Rural Investment Act of 2002 will raise the corn support price from the current \$1.89/bushel to \$1.98/bushel (\$78/Mg) this year and next (University of Illinois, 2002). The average prices of \$80/Mg for corn and 40 cents/ha-mm were used in this analysis. The prices of anhydrous ammonia, the most common source of nitrogen fertilizer used in corn production, is derived from natural gas. Increases in the prices of natural gas have caused N-fertilizer prices to soar. The prices of anhydrous ammonia were about 22-25 cents/lb in January 2001 as compared with 12-13 cents/lb in January 2000 (Thiesse, 2002). The prices of water and corn vary considerably from year to year and from place to place (mostly for the price of water), they are changed in the sensitivity analysis to see how changes in relative prices will affect the optimal levels of irrigation and returns to irrigation.

### ***Estimation of Production Functions***

The following quadratic function was estimated using the least squared methods:

$$Y = \alpha + \beta W + \gamma W^2 \quad (1)$$

where Y = yield,

W = amount of water including irrigation water and rainfall,

$\alpha$ ,  $\beta$ , and  $\gamma$  = coefficients.

Initially, we pooled the data to estimate an aggregated production function for each year with a dummy variable to account for variation in nitrogen treatment. But the estimated coefficient of the dummy variable was not statistically significant at the 5% level and our scientists believed that corn responds differently with different level of nitrogen fertilizer application. Therefore, we decided to estimate two separate production functions for each year, one for 225 kg/ha (H) and the other for 135 kg/ha (L). The estimated production functions for the three years by the two N-fertilizer treatments are presented below.

$$1999L: Y = 6.320^{**} + 0.03193^{**}W - 0.00005651^{**}W^2 \quad R^2 = 0.6506, n = 86$$

$$1999H: Y = 6.7013^{**} + 0.02483^{**}W - 0.00003539^{**}W^2 \quad R^2 = 0.6369, n = 82$$

$$2000L: Y = 4.854^{**} + 0.03979^{**}W - 0.00007451^{**}W^2 \quad R^2 = 0.6324, n = 91$$

$$2000H: Y = 4.428^{**} + 0.04259^{**}W - 0.0007804^{**}W^2 \quad R^2 = 0.5137, n = 76$$

$$2001L: Y = 9.777^{**} + 0.01551^{**}W - 0.00003887^{**}W^2 \quad R^2 = 0.1154, n = 92$$

$$2001H: Y = 9.372^{**} + 0.01572^{**}W - 0.00003243W^2 \quad R^2 = 0.1338, n = 76$$

The symbol L denotes N-fertilizer application of UAN = 135 kg/ha and H, UAN = 225 kg/ha. The coefficients for all variables have the expected signs and the levels of statistical significance are indicated by \* = 5 percent and \*\* = 1 percent.

### *Optimal Levels of Irrigation*

Biological scientists and farmers tend to determine the levels of irrigation water that maximize yields, while economists determine the levels of irrigation water that maximize profits. Once the water production function is estimated, the slope of the production function can be obtained by taking the derivative of  $Y$  with respect to  $W$ ,  $dY/dW$ , which is the marginal physical product (MPP) of irrigation water. It represents the amount of crop yield that can be obtained by a small unit increase in irrigation water. As more irrigation water is applied, the yield will increase but at a decreasing rate, and eventually a maximum will be reached. At that point, the slope of the production function is zero. Thus, the level of irrigation water that maximizes yields can be obtained by equating the MPP with zero, or  $dY/dW = 0$ . Unless irrigation water is free, the yield-maximizing level of irrigation will not give maximum profit. The profit maximization condition can be obtained by equating the MPP with the ratio of the price of water to the price of corn.

Given a production function (1), the profit maximization condition can be obtained by equating MPP with the price ratio:

$$MPP = \frac{dY}{dW} = \beta + 2\gamma W = \frac{r}{p} \quad (2)$$

where  $p$  is the price of corn and  $r$  is the price of water. The optimal level of irrigation water for profit maximization can be obtained by solving equation (2) for  $W$

$$W = \frac{r}{2\gamma p} - \frac{\beta}{2\gamma} \quad (3)$$

which is the derived demand function for water. Alternatively, the profit-maximizing condition can be obtained by equating the value of the marginal product (VMP), which is equal to the MPP times the price of corn, with the price of water.

## RESULTS AND DISCUSSIONS

Recall that the estimated production function for 1999 with UAN = 225 is

$$Y = 67.013 + 0.02483W - 0.00003539W^2$$

At the current price of corn at \$80/Mg and the price of water in South Carolina at 40 cents/ha-mm,

$$VMP = 1.99 - 0.005662W.$$

At zero irrigation, the VMP is \$1.99/ha-mm. That means a 1 ha-mm of irrigation water will increase gross margins \$1.99/ha. The VMP at zero irrigation can be used to determine whether it will pay to initiate irrigation. As long as the price of water is less than \$1.99/ha-mm, it is profitable to start irrigation. Since MPP is diminishing as more irrigation is applied, eventually the point where  $VMP = r$  will be reached. This is the level of irrigation that maximizes profits. Further irrigation application after this point will cause profits to decline. Farmers can use the VMP to determine whether it is profitable to start irrigation and to continue irrigation.

Table 1 shows the levels of irrigation water, corn yields, and gross margins under profit-maximizing and yield-maximizing strategies for 1999, 2000, and 2001 by two N-fertilizer treatments at the current prices of corn and water in South Carolina. At the current water price of 40 cents/ha-mm and corn price of \$80/Mg, profit-maximizing strategies conserved more water and produced much larger gross margins than the yield-maximizing strategies.

For example, in 1999H, the profit-maximizing strategy irrigated 280 ha-mm of water to produce \$197/ha of gross margins, whereas the yield-maximizing strategy used 351 ha-mm of water to produce only \$173/ha of gross margins, even though the yield difference was relatively small. The differences in optimal levels of irrigation water and gross margins between the two strategies become even more significant when the relative water/corn price ratios increase.

TABLE 1. Optimal levels of irrigation water and gross margins under current prices of corn and water.

Year and N level	Irrigation water (ha-mm) under		Optimal yields (Mg) under		Gross margins (\$/ha) under	
	Profit-max	Yield-max	Profit-max	Yield-max	Profit-max	Yield-max
2001H	165.28	242.37	11.08	11.28	239.81	214.30
2001L	135.19	199.51	11.39	11.55	260.16	238.87
2000H	240.84	272.87	10.16	10.24	184.05	173.44
2000L	233.46	267.01	9.71	9.80	174.71	163.61
1999H	280.16	350.81	11.19	11.37	196.82	173.44
1999L	277.79	336.05	11.26	11.41	199.69	180.41

### *Sensitivity Analysis*

The optimal levels of irrigation water that maximize profits depend heavily on the relative prices of water and corn and both water and corn prices varied considerably over time and across the regions (especially for water). As indicated earlier, corn prices have fluctuated from \$59 to \$128 in the last 20 years. The price of water in South Carolina is relatively cheap compared to the water shortage areas such as California, where the asking price of water by the Water Bank was \$175/acre-foot (\$1.42/ha-mm) in 1991 (McCann et al., 2002). To see the effect of changing relative water/corn prices on the optimal levels of irrigation water and gross margins, we used different combinations of water prices at 30, 40, and 50 cents/ha-mm and corn prices of \$70, \$80, and \$90/Mg. The results are shown in Table 2.

Higher water/corn price ratios decreased the optimal levels of irrigation water and the gross margins. In 1999H, for example, the optimal irrigation water and gross margins under the water price of 30 cents/ha-mm and the corn price of \$90/Mg, are 333 ha-mm and \$322/ha, respectively. When the price of water increased to 50 cents/ha-mm and the corn price decreases to \$70/Mg, the optimal level of irrigation water dropped to 69 ha-mm and the gross margins decreased to \$25/ha.

### *The Price Elasticity of Demand for Water*

The elasticity of demand for water (E) is defined as a percentage change in the profit-maximizing quantity of irrigation water in response to a percentage change in the price of water. It measures the responsiveness of irrigation water quantity to changes in the price of water. It is defined as

TABLE 2. Optimal levels of irrigation water and gross margins under alternative water/corn price ratios.

Year and N level	Corn price (\$/Mg)	Irrigation water under water price at			Gross margins under water price at		
		30 cent/mm	40 cent/mm	50 cent/mm	30 cent/mm	40 cent/mm	50 cent/mm
2001H	70	143.10	132.34	125.43	125.76	101.53	77.29
2001H	80	252.89	239.81	229.93	238.54	214.30	190.06
2001H	90	363.50	348.75	336.71	351.31	327.07	302.83
2001L	70	157.82	149.11	143.62	143.36	123.41	103.46
2001L	80	270.80	260.16	252.18	258.82	238.87	218.92
2001L	90	384.46	372.42	362.65	374.28	354.33	334.38
2000H	70	105.54	83.86	63.77	98.34	71.05	43.77
2000H	80	206.69	184.05	162.72	200.73	173.44	146.16
2000H	90	308.19	284.84	262.62	303.12	275.83	248.54
2000L	70	99.88	79.04	59.89	92.33	65.63	38.93
2000L	80	196.56	174.71	154.26	190.31	163.61	136.91
2000L	90	293.59	271.02	249.63	288.29	261.58	234.88
1999H	70	110.72	87.99	68.79	94.84	59.76	24.68
1999H	80	221.67	196.82	174.90	208.52	173.44	138.36
1999H	90	333.38	306.99	283.09	322.20	287.12	252.04
1999L	70	115.81	89.63	69.12	105.86	66.34	32.73
1999L	80	224.86	199.69	176.94	214.01	180.41	146.80
1999L	90	337.30	310.87	286.48	328.08	294.48	260.87

$$E = \frac{\partial W}{\partial r} \times \frac{r}{W} \quad (4)$$

Differentiating W in (3) partially with respect to r yields

$$\frac{\partial W}{\partial r} = \frac{1}{2\gamma p} \quad (5)$$

Substituting (3) and (5) into (4) gives

$$E = \frac{r}{r - p\beta}$$

which is always negative, because the slope is negative and the prices of corn and water are positive. When the absolute value of  $E$  is 1, it's elastic; when it is zero, inelastic. The value of  $E$  increases as the price of water increases and decreases as the price of corn increases. In 1999H, for example, when the price of water is \$90 and the price of water is 30 cent/ha-mm,  $E = 0.16$  (in absolute value), which is very inelastic. It indicates that demand for irrigation water will decrease only 0.16 percent with a 1 percent increase in the price of water. When the price of water increased to 50 cent/ha-mm and the price of corn dropped to \$70/Mg, the elasticity of demand increases to 0.4. Table 3 shows the demand elasticities for 1999, 2000, and 2001 by high and low N-fertilizer treatments under alternative relative price ratios.

### CONCLUSIONS

Water is a precious resource and is used in many competing industries. To use water efficiently, the plant response to water, or the production function, is

TABLE 3. Demand elasticities of water under alternative prices of corn and water.

Year and N level	Corn price	Irrigation water price		
	(\$/Mg)	30 cent/mm	40 cent/mm	50 cent/mm
2001H	70	-0.37	-0.57	-0.83
2001H	80	-0.31	-0.47	-0.66
2001H	90	-0.27	-0.39	-0.55
2001L	70	-0.38	-0.58	-0.85
2001L	80	-0.32	-0.48	-0.67
2001L	90	-0.27	-0.40	-0.56
2000H	70	-0.11	-0.15	-0.20
2000H	80	-0.10	-0.13	-0.17
2000H	90	-0.08	-0.12	-0.15
2000L	70	-0.12	-0.17	-0.22
2000L	80	-0.10	-0.14	-0.19
2000L	90	-0.09	-0.13	-0.16
1999H	70	-0.21	-0.30	-0.40
1999H	80	-0.18	-0.25	-0.34
1999H	90	-0.16	-0.22	-0.29
1999L	70	-0.16	-0.25	-0.33
1999L	80	-0.15	-0.21	-0.28

needed. In this paper, we estimated six production functions, two N-fertilizer treatments for each year in 1999, 2000, and 2001. Optimal levels of irrigation and gross margins under profit-maximizing and yield-maximizing strategies were computed.

At the current prices of corn and water in South Carolina, profit-maximizing strategies conserved much less water and produced much larger gross margins than the yield-maximizing strategies. For example, in 1999H, the profit-maximizing strategy irrigated 280 ha-mm of water to produce \$197/ha of gross margins, whereas the yield-maximizing strategy used 351 ha-mm of water to produce \$173/ha of gross margins. The differences in optimal levels of irrigation water and gross margins between the two strategies become even more significant when the relative water/corn price ratios increase.

To find out how demand for irrigation water responds to changes in water prices, demand functions for water were derived and demand elasticities of water were computed. At the current prices of water and corn, the demand elasticities were inelastic, which means that irrigation was not very responsive to changes in the price of water. However, at high water prices, demand for irrigation became more responsive to changes in water prices.

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